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Scientific and Technical Intelligence Report

*Soviet Research Related to the Development of an
Over-the-Horizon Detection System*

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Scientific and Technical Intelligence Report

SOVIET RESEARCH RELATED TO THE DEVELOPMENT OF AN
OVER-THE-HORIZON DETECTION SYSTEM

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Project Officer



OSI-STIR/68-18

August 1968

CENTRAL INTELLIGENCE AGENCY
DIRECTORATE OF SCIENCE AND TECHNOLOGY
OFFICE OF SCIENTIFIC INTELLIGENCE

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PREFACE

This report reviews and analyzes Soviet research and capabilities in areas related to the development of an over-the-horizon detection system. It is based on an external contract, and was prepared solely by the Office of Scientific Intelligence and coordinated with the Directorate of Intelligence. The cutoff date of the information is 1 June 1968.

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TECHNICAL FOREWORD

Over-the-horizon detection of missile launch and reentry requires the use of high-power transmitters to propagate high-frequency energy (signal) to distances well beyond the horizon. When this signal is reflected and scattered by any of a large variety of moving targets, such as missiles, missile-wakes, or aircraft, it experiences a recognizable shift in frequency imparted by the target's motion. The signal is then received at a site by relatively sophisticated equipment where the Doppler-shifted signature is resolved from the general signal environment.

The receiver site can be collocated with the transmitter (back-scatter detection), or located beyond the target (forward-scatter detection), or placed anywhere else in azimuth relative to the target (polystatic detection). The transmitter may be a cooperative one, in which case it is specifically designed as part of an over-the-horizon detection system; or the transmitter may be a noncooperative one, in which case the system utilizes the output of any high frequency transmitter suitably located with respect to a specific target.

The transmitter may be operated in single-, multiple-, or random-frequency pulse, simple or compressed pulse, or in a continuous wave mode. In short, OTH detection systems can employ any one of a large variety of transmitters and receivers and can use an even larger variety of geometries.

A research and development group competent in the field of OTH detection must contain personnel who are expert in several different scientific and technological areas. These areas include high-frequency transmitters, receivers, and antennas, as well as the general field of ionospheric physics including propagation, absorption, dispersion, and the radio frequency phenomenology of missile launch and reentry at high frequencies.

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SOVIET RESEARCH RELATED TO THE DEVELOPMENT OF AN OVER-THE-HORIZON DETECTION SYSTEM

PROBLEM

To determine the USSR's capability to develop an over-the-horizon radar detection system and the approach most likely to be used.

SUMMARY AND CONCLUSIONS

There is no direct evidence of an over-the-horizon (OTH) radar detection system in the USSR, but Soviet research in each of the principal scientific and technological areas having possible OTH applications has been identified. Soviet knowledge and state-of-the-art in these areas were adequate for the development of OTH radar in the mid-1960's.

The Soviets are giving particular emphasis to virtually real-time methods of reducing ionospheric sounding data, which is necessary in calibrating the range and angle of signal returns in an OTH system. A significant field of HF propagation under study is the determination of the backscattering cross section of the earth's surface.

Soviet work on HF antenna design further indicates the likelihood that research and development of OTH radar equipment have been performed. Of particular importance are several papers on optimal antennas employing electronic scanning for use in direction finding. Research in the key problem area of HF antennas with dual or selectable polarization has also been observed. An electronically steered two-antenna HF radio-telescope has been developed by the Institute of

Radio Physics and Electronics, Academy of Sciences, Ukrainian SSR.

Antennas having an electronic beam steering capability both in azimuth and elevation probably will be employed by the Soviets in an OTH radar, at least in receive modes. Special techniques, such as nonuniformly spaced arrays, may also be used to control the sidelobe structure to help suppress interference. In addition, the receiver antennas may be polarized in two planes since the transmitted waves undergo depolarization from several sources and polarization rotation due to the Faraday effect.

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The applicability of work on detection and signal processing to OTH radar is less easily determined. Numerous Soviet authors have written on concepts that have broad application to radar and communications systems, including sequential detection, digital detection, multi-channel equipment, asynchronous detection, phase-locked loops, and measurement systems. The design of a receiver for an OTH radar, however, does not require a breakthrough in technology, but rather the application of existing technology. The Soviets have demonstrated competence in each of the types of receivers and detectors that could be used in an OTH radar. Soviet research indicates that digital detection concepts might be employed in an improved Soviet OTH radar.

Soviet scientists are carrying out research and experimentation in the whispering gallery, or ricochet, mode of the HF radio propagation. The unique feature of this mode is low-attenuation propagation over very long paths between the E and F layers of the ionosphere. The data show that this mode has enabled communications with satellites to be maintained for over 50 percent of the time under non-line-of-sight conditions. The Soviets report that propagation losses in this mode are less than free-space losses for equivalent radar-

to-target distance of between 12,000 and 20,000 km. Soviet scientists also report that excitation of the mode is achieved via the sporadic-E layer electron-density gradients in the vicinity of the ground terminal. The presence of this sporadic layer can be ascertained by conventional ionospheric sounders.

There is some evidence to suggest Soviet attempts to overcome the problem of reliably exciting a whispering gallery mode by artificially creating an ionospheric tilt into which this mode can propagate. Since propagation conditions in the ionosphere near the polar region are often unfavorable and would severely limit the operation of a Soviet OTH multi-hop radar in this area, the Soviets might decide to avoid this area of disturbance by using whispering gallery propagation, but there is no evidence of this.

The organization most prominent in HF propagation is the Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation, USSR Academy of Sciences (IZMIRAN). The next most active organization is the Moscow State University. In antenna research and development, two groups appear to play major roles. One group is associated with the Institute of Radio Physics and Electronics, Academy of Sciences, Ukrainian SSR. The other is associated with the Scientific-Research Radio Physics Institute, Gorkiy University.

DISCUSSION

IONOSPHERIC SOUNDING RESEARCH

Any HF system that requires the propagation of electromagnetic energy over long distances must be concerned primarily about the condition of the ionosphere. Whether one uses a conventional multi-hop mode, or the whispering gallery mode, or a combination of the two, one must know the height and density of the E and F layers to determine what frequencies are required in order to place the HF energy in the desired region at long distance from the transmitter. The measurement technique that has come into prominence is that of oblique backscatter from the ground, which is a method for sounding the ionosphere up to 6,000 km in ground range in front of a transmitter. A

swept-frequency pulse is used to determine the height of the ionospheric layers by observing the time delay for ground backscatter echoes to reach the receiver, which is usually collocated with the transmitter. In recent years Soviet unclassified literature has shown great interest in this technique.

As early as 1960 K. M. Kosikov reported that the use of backscatter observation in conjunction with radio communication yields almost all the necessary information about the state of radio wave propagation conditions over long distances, often over the whole earth.¹ He stated that backscatter observation, if correctly applied, would contribute to an increase in the effectiveness of long-distance radio communication and radio broadcasting and to

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a more systematic utilization of the spectrum of radio frequency on the 6- to 30-MHz band.

In 1964 V. A. Baranulko published *Characteristics of the Propagation of Radio Waves*, which described the experimental determination of HF communication working frequencies by the oblique backscatter sounding method.² It included data on the effects of winds in the ionosphere and made recommendations for their being taken into account in practical propagation applications. Although the book is intended for students in military radio schools and for communication officers, it is also applicable to the prediction of usable frequencies for OTH detection.

In 1965 G. P. Tsirs, in a monograph concerned with the aurora, geomagnetic perturbations, and the high latitude ionosphere, described an experiment using backscatter sounding of the ionosphere at Murmansk, over the Murmansk-Rugozero-Leningrad communication path.³ The purpose of the experiment was to compare the results of backscatter techniques for sounding the ionosphere with the more conventional vertical sounding results that were simultaneously obtained along the path. The experiments were carried out using pulse widths of 1.0 and 2.8 ms and a 20 kw transmitter. Data were reported for frequencies from 5 to 13 MHz. Experiments were carried out when there were E, sporadic-E, and F₁ and F₂ layers. The article concluded that, as a result of comparing the vertical sounding data with the backscatter data, it is possible to observe backscatter echoes with ground ranges of the order of 400 to 6,000 km even in the presence of large perturbations of the ionosphere. Under winter ionospheric conditions, good agreement between the vertical and oblique sounding data from the F₂ layer was noted. It was also concluded, from a comparison of the oblique and vertical data, that under summer ionospheric conditions more exact and systematic observations and measurements were needed to produce agreement.

Perhaps the best known unclassified document concerning backscatter results is a book by N. L. Kabanov and B. L. Osetrov published in 1965.⁴ It treated the theoretical and experimental aspects of backscatter sounding, as well as practical applications, and referenced the results of investigations including those of many Western scientists. Kabanov first empirically treated the characteristics

of one-hop backscatter (obtained at ground distances up to 2,500 to 3,000 km) as a function of the transmitted pulse frequency, the time of day, and month of the year. These characteristics were categorized and the ionospheric conditions, as well as times of occurrence, giving rise to them were delineated. The potential for selecting reliable communication link frequencies in each category was stated. Multi-hop backscatter was then considered up to ground ranges of 12,000 km, and experimental backscatter results compared favorably with field-intensity measurements made at 6,300 km away from the transmitter, as well as with median usable frequency values for specific paths. The variation of backscatter characteristics with transmitting azimuth and the effects of irregularities, such as sporadic-E, F layers diffusion, and meteors were briefly considered.

A relatively large section of the book was devoted to the derivation and use of expressions to predict the areas illuminated during backscatter sounding and backscatter station parameters. Methods for using backscatter soundings to determine the maximum usable frequency, condition of the intervening ionosphere, and absorption along a communication path were presented. Finally, the transmitting and receiving equipment and antennas required for backscatter sounding were described.

In a paper presented to the Twenty-third All Union Scientific Session commemorating the Fiftieth Anniversary of Soviet Power and Radio Day, results were given of experiments conducted at Irkutsk during the summer months of 1965.⁵ The experiments dealt with backscatter sounding at 17 MHz and the analysis of the recorded data. The results were said to have confirmed the conclusion that it is realistically possible to record scattered reflections of backscatter soundings from the surface of the sea at smaller angles of incidence than from the land. The scattering surfaces were the sea to the east of Irkutsk and the mountains of the Himalayan Range to the west-southwest. This type of work could have application in the determination of terrain features illuminated during backscatter sounding and would be of particular importance in any research pertaining to an OTH detection system.

An article by R. G. Minullin and B. K. Mikhaylov gives data on observations performed in 1963 on

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reflected signals from the sporadic-E layer along a 1,600 km route.⁶ The amplitude of the reflected signal frequently exceeded the level of the signal during meteoric reflection on the same route. Under multibeam conditions, the difference in delay was basically 8 to 12 ms. Observations of the shape of echo pulses made it possible to conclude that in the absence of multibeam conditions the sporadic-E layer passband is wider than 2 MHz.

IONOSPHERIC SIGNAL PROPAGATION

The various aspects of the propagation of electromagnetic waves in the ionosphere are of paramount interest to HF communication systems as well as to OTH detection systems. Effects, such as refraction, attenuation, and multipath propagation, must all be considered. Over the past few years some work in this area has been conducted by Soviet scientists.

V. A. Adrianov and N. A. Armand in "Diffraction of Radio Waves Around the Earth in the Presence of a Reflecting Layer in the Atmosphere," developed a mathematical treatment of multi-hop and whispering gallery modes of propagation.⁷ Dispersion relations were obtained for both of these types of wave propagation. The paper concluded that the presence of a discontinuity in the coefficient of refraction brings about radio-wave reflection from a layer or the creation of waves that propagate along a layer at some altitude in the ionosphere. This discontinuity was considered as an inhomogeneous layer.

In 1964 T. S. Kerblay and Ye. M. Kovalevskaya in "Determination of the Distance of the Hop of a Radio Wave Propagating in a Horizontally Inhomogeneous Ionosphere" presented a solution to the problem of determining a central angle θ (corresponding to the angle subtended at the center of the earth by the path of a radio wave in the ionosphere) under the assumption that the ionosphere is horizontally inhomogeneous.⁸ Electron density was represented in spherical coordinates as a function of two variables. An integral was developed that could be solved either analytically or graphically. Tables were included for frequencies of 5 to 20 MHz to allow one to compute the skip distance for a ray passing through the ionosphere.

It was noted near the end of the article that these computations, whose purpose was to estimate the effects of the horizontal inhomogeneity of the ionosphere, were made under several simplifying assumptions. Some of these assumptions, such as neglecting the earth's magnetic field, are permissible in estimating maximum usable frequency (MUF) and skip distances, but others must be eliminated in more detailed computations.

In a later article the authors computed the propagation paths for frequencies of 20 and 30 MHz also in a horizontally inhomogeneous ionosphere.⁹ Use was made of an assumed parabolic variation of ionization with height and the horizontal inhomogeneity was accounted for by the gradient of critical frequency, the half-thickness, and height of the ionization maximum of the F₂ layer. An illustration was given in which the MUF was computed for a single-hop radio link with allowance for horizontal ionization gradients.

N. S. Gavrilova, O. N. Loginova, and G. I. Makarov reported on theoretical solutions of Maxwell's equations applicable to the propagation of radio waves along an unbounded, smooth layer.¹⁰ Numerical integration was used to evaluate the normalized wave admittance, from which the reflection coefficient for various angles of incidence was obtained so that the ground area illuminated could be determined.

Propagation in the ionosphere was also studied by G. I. Makarov and V. V. Novikov whose purpose it was to clarify complications that result from the curvature of the earth and the curvature of the ionosphere and to determine the boundary between the two.¹¹ Several models of the earth-ionosphere geometry were considered, and a comparison of phase velocities in radio-wave propagation was made.

V. B. Kashkin and Zh. N. Vetshev described an instrument for the measurement of statistical characteristics of diversity signal reception.¹² The authors described a two-channel plus height analyzer intended for the determination of the one-dimensional and two-dimensional probability distributions with respect to the levels of two random signals. The purpose of the analysis was to make it possible to estimate the advantage offered by diversity reception with automatic selection and to find the signal correlation coefficient. In another

article Kashkin considered the dependence of the correlation coefficient p on the diversity parameter in ionospheric scattering applied to highly directional antennas in which the incident electromagnetic field at the aperture was partially decorrelated.¹³ A general formula was derived for p in the case of spatial separation of antennas, and graphs were presented for the values of p at different values of antenna aperture, measured in wave lengths. Losses in antenna receiving gain due to the decorrelation across the antenna aperture resulting from ionospheric scattering were investigated. It was shown that narrowing the directivity pattern of the receiving antenna led to a slowing down in the decrease of p with the diversity parameter and to a decrease in the fluctuations of the received signals and, hence, to increased gain.

An article by Yu. K. Kalinin and I. L. Vsekhvatskaya proposed a method of computing signal intensity along a short-wave link on the basis of data from the existence of dead zones in short-wave communications using the simplest concepts of geometrical optics. An elementary function of the link T was introduced and used to perform the main computations.¹⁴ Both single-hop and multiple-hop propagation paths were considered, and a possible method of interpreting data from oblique backscatter returns on long links was proposed.

A paper by T. A. Gaylit and V. D. Gusev was on a theoretical study of diffraction from a screen assumed to be at ionospheric height;¹⁵ their interest was in the spatial-energy-spectrum function of the scattered signal at the ground. The authors included a coherent component and found that the spectrum of the square of the ground amplitude contained an oscillatory term. A spectral analysis was carried out experimentally.¹⁶ Another paper by Gaylit described a phase meter for measuring the phase and amplitude of the reflected wave.¹⁷ The output is recorded digitally and analyzed by computer. The author found that 27 percent of the results imply the presence of irregularities larger than a Fresnel zone, in addition to smaller irregularities. It is not clear what objectives the author had in mind, other than basic research. The recording techniques would be of use in other studies, such as study of signal changes in oblique paths in relation to missile effects, explosions, and the like.

IONOSPHERIC DATA REDUCTION TECHNIQUES

The application of modern techniques of digital automatic data reduction to the conversion of experimental ionospheric records to forms useful for scientific analysis and prediction of propagation conditions is important from a communications and an OTH detection viewpoint.

With respect to the problem of determining the distribution of electron density with height in the ionosphere from ionogram data, which may be described as the fundamental problem in the analysis of ionospheric data, one of the principal workers has been B. S. Shapiro.¹⁸⁻²¹ His work, based on the work of Jackson of the United States, displays some interesting features in the true height reduction program. Among these is an interpolation procedure that may be applied to the ionogram in sections so that the amount of scaled data need not be excessive in regions where the virtual height curves are smooth, and yet closely spaced points are available for application to the true-height inversion routine. In addition, the program incorporates a number of checking features that are applied to the incoming data to ensure consistency. Data reduced to true-height distributions in this way are useful for various scientific investigation of the ionosphere. However, the data could also be of significance in detection schemes, where it is important to be able to reconstruct the wave path of a ray in the ionosphere with precision so that a target location can be inferred from measured angles of arrival and pulse delay times. It has been clearly demonstrated that the Soviets have an adequate solution to the true-height reduction problem.

True-height reduction is not the only aspect of ionospheric data reduction that has been automated. The problem of automatically digitalizing virtual-height frequency data was discussed by A. L. Galkin,²² and by Galkin and N. I. Dvinskikh.²³ The approach they described works with successive pulses of a swept-frequency ionogram and separates out the noise and signal components by making use of an averaging technique that compares successive sweeps. The significance of this automatic approach is that it is potentially capable of being used in real- or near real-time, without transcription of data in graphical form. In addition to mak-

ing possible the treatment of large amounts of ionospheric data for routine purposes, the technology suggests sophistication in the treatment of ionospheric displays, that might also be applied to backscatter radars for rapid analysis and calibration of the results of sounding in terms of known ionosphere layer characteristics.

The approach of Galkin may be contrasted to that of a related study by E. L. Afraymovich in which he described an automatic multichannel system for recording and processing data on the inhomogeneous structure of the ionosphere.²⁴ The system includes recording equipment, a magnetic tape memory, digital computer input equipment, and computer programs for the insertion and processing of experimental data. The system has a simple recording unit and a high noise immunity link with the digital computer, an effective computer input speed of the order of 1,000 numbers per second, and has a practically unlimited effective memory. It can operate with any digital computer at a speed of no less than 2,000-5,000 operations per second, which makes it possible to process the same collection of records on different digital computers. The above system forms part of a complex developed for the study of the ionosphere. Other parts include: i) a system for processing the results of vertical panoramic ionospheric sounding data; ii) a 64-channel system for investigating the frequency dependence of various parameters (frequency correlation, the spectrum of a signal reflected from the ionosphere, radio wave absorption, etc.); and iii) a recording and data processing system for the study of statistical signal characteristics in oblique sounding of the ionosphere. This automatic recording and data processing system forms part of an installation for multiple-frequency sounding of the ionosphere as described by E. L. Afraymovich and G. M. Kudelin.²⁵ The installation operates in a frequency scanning range of from 50 kHz to 20 MHz. The equipment makes use of a SP-3 ionospheric station.²⁶ This station is of East German origin and has the following characteristics: i) pulse power of 20 kw, ii) sweep time of 30 seconds, iii) altitude markers of 100 km to a maximum of 750 km, and iv) four mutually perpendicular rhombic antennas. Technology of this nature could have important applications to the rapid reduction and calibration of oblique backscatter and OTH detection records.

Work on computerization has not been limited to data scaling and inversion for true heights. The computation of the maximum usable frequency for communication between two points has been computerized by Ye. M. Kovalevskaya.²⁷ This work is not based on direct analysis using measured experimental data, but on predictions using such factors as the solar zenith angle and sunspot number. In view of the extent of computer application to ionogram reduction, the automatic determination of maximum usable frequencies from the data would appear a logical step, but a description of such work was not found. It could have very direct connections to OTH detection applications, where accurate real-time data would be valuable; and the methods of computation would relate closely to methods of oblique sounder data reduction. The work by Kovalevskaya, however, does indicate application of computer technology, at least to the prediction problem, which is again of importance from a planning point of view.

RESEARCH ON THE WHISPERING GALLERY PROPAGATION MODE

Recently there has appeared in Soviet journals an increasing number of technical papers on the subject of long-distance, HF radio propagation involving the so-called "whispering gallery" or "ricochet" mode.

The development of reliable application of this mode of propagation would be of value in ground-to-satellite communication links or satellite-to-satellite links. However, there is also the possibility of Soviet development of this propagation mode for OTH radar with the capabilities to detect burning missiles and nuclear bursts.²⁸

T. L. Kerblay discussed ionospheric slopes and electron-density gradients and their influence on long-distance propagation and MUF.²⁹ Kerblay mentioned that measurements of effective ionospheric slope angles indicate that daily changes average ± 2 degrees, while occasionally the slope increases to ± 5 degrees, suggesting that long-range propagation without involving multiple ground reflections probably occur quite frequently. Another brief mention of this propagation mode was made by Adrianov and Armand,⁷ who identified this mode with the analogous sound propagation mode, called the "whispering gallery" mode by its dis-

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coverer, Lord Ralyleigh, in 1914. This paper considered primarily the theoretical aspects of the problem of calculating maximum usable frequencies and the resulting attenuation over the path.

Kerblay's work was expanded in a paper by L. N. Lyakhova, who analyzed the focusing effect of the curved ionosphere using a simple geometric treatment and calculated the variation in signal strength of a satellite transmitter as a function of range for a typical case.³⁰ The resulting data matched remarkably well with previously measured signal strength data.³¹ The data explained the observed increasing signal strength from 12,000 to 20,000 km. Two papers by Sh. G. Shlionskiy discussed satellite communications involving the mode of propagation. The first paper described the ray theory approach to HF ionospheric propagation and showed simple curves of MUF and path losses computed using the theory.³² The second paper used the theory for the specific case of "above-ground trajectories" of the ray of satellite communications.³³ Neither of these papers, however, goes beyond an elementary treatment of the theory to explain qualitatively observed satellite signal characteristics and to suggest that the Soviets are maintaining their interest in such low-attenuation propagation modes.

A paper by T. L. Berbasov, T. S. Kerblay, Ye. M. Kovalevskaya, and L. N. Lyakhova discussed the finding that communications at 20 MHz with the Vostok 1 through 6 spacecraft could be maintained from the Soviet Union about 50 percent of the time that those spacecraft were below the F layer, whereas calculations of conventional multihop propagation indicate that communication should be possible only 12 to 70 percent of the time, depending upon the level of sunspot activity.³⁴ The finding was examined and explained in terms of a "rebound" mode of propagation from the F layer, with ground launching of the mode facilitated by sporadic-E layer inhomogeneities in the vicinity of the ground terminal. This paper showed only sample data to illustrate the description of the analysis, but suggested that much more detailed data and analysis had been made to justify the conclusion reached. The conclusion was that sporadic-E propagation is the mechanism for

launching this low-attenuation mode, and therefore statistics can be developed for mode reliability and optimum frequencies can be determined from conventional sporadic-E sounding measurements.

Recent Soviet work has been concerned with the sporadic-E layer. A paper by A. A. Starovarov studied the relationship between tidal forces and cutoff frequencies (f_o) of the sporadic-E layer.³⁵ The author showed from experimental data that the density of the sporadic layer is rather sensitive to a change in tidal forces. The sporadic-E layer parameter can be expected to vary with a periodicity of 27 days. T. S. Kerblay concluded that sporadic-E and auroral absorption are of the same nature.³⁶ This finding was based on the relationship obtained between sporadic-E layer cutoff frequency and the magnitude of absorption in the auroral zone. The probability of appearance of sporadic-E and the degree of magnetic disturbance at various latitudes was examined by Ya. M. Shvarts and S. L. Andreyeva.³⁷ The authors conclude that the problem is complex and needs further study.

All of the above work on the occurrence of the sporadic-E layer would be of interest in the problem of reliably launching a whispering gallery mode for communications and as an OTH propagation medium. Another method of overcoming the problems associated with reliably launching this mode is to artificially disturb the ionosphere, that is, to create a tilt into which the mode could propagate. Work by A. V. Gurevich might have application along these lines.³⁸ A high power radio beam whose frequency is close to the critical frequency of the maximum reflecting layer of the F_2 region will reduce the local electron content of this region. In effect one would create an artificial tilt, or gradient, in the ionosphere which might allow a whispering gallery mode to propagate. Transmitter power and antenna configuration referred to by Gurevich are well within the Soviet capability. Propagation conditions near the polar region are often unfavorable and would severely limit the operation of a Soviet OTH multihop radar in this area. Whispering gallery propagation might possibly offer a solution by avoiding the area of disturbance along the propagation path.

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RADAR EQUIPMENT R&D

Antennas

Antennas designed for use in an OTH radar system have certain features imposed on them by operational and functional requirements. The antennas can be expected to be physically quite large to achieve high gain for detection and to have suitable directivity for angular accuracy and good beam structure for discrimination against sources of interference. Electronic beam steering will probably be employed by the Soviets, at least in receive modes. Special techniques may be used to control the sidelobe structure to help suppress interference. Elevation as well as azimuth steering may be used to facilitate illumination of desired search volume. The receiver antennas may be polarized in two planes since the transmitted waves undergo depolarization from several sources and undergo rotation due to the Faraday effect.

The USSR has built and deployed several types of HF antennas which meet several of the requirements stated above.³⁹ Although no evidence is available to definitely connect any of these antennas with an OTH system, some of them are suspect.⁴⁰

One Soviet author, L. G. Sodin of the Institute of Radio Physics and Electronics of the Ukrainian SSR, has written in several areas which could be related to the development of an OTH antenna. Together with Yu. M. Bruk, Sodin wrote in detail on a novel antenna beam steering concept.⁴¹ Discrete time delays are generated probably through the use of tapped delay lines. The delay is performed in tiers somewhat resembling a corporate-feed structure. This results in a significantly reduced requirement for control switches. The paper also investigated the pattern errors, mainlobe displacement, and gain loss resulting from phasing errors. Equations were derived for the number of switches and coarseness of adjustment of time delay for specified levels of pattern degradation. This would be a very useful paper for the designers of wideband HF steerable phased arrays. This concept was probably used in the broadband HF radiotelescope described by these authors in another paper.⁴² Sodin and I. L. Verbitskiy derived expressions for the directivity of a linear antenna array with an optimal pattern according to Dolph.⁴³ Nonisotropy of the radiators arranged at any distance is taken into account.

Bruk analyzed an electrically steerable array type antenna in which the impedances of the radiating elements were assumed to be nonidentical.⁴⁴ The effects of correlated fluctuations of reflection factors upon mean directional pattern, mean directive gain, mean radiation efficiency, and mean power gain of the practical antenna were evaluated on the basis of probability. It was found that: i) As compared to the ideal system, the practical antenna system has its parameters dependent on the direction of phasing and length of channels; the directional pattern is more distorted; the directive gain is lower; however, the power gain is higher. ii) For both types, ideal and practical, the energy reflected by radiating elements is completely lost through absorption or radiation in undesirable directions.

Yu. M. Zhidko of the Scientific-Research Radio Physics Institute at Gor'kiy University has written on problems relative to OTH radar, regarding the application of phase monopulse to active and passive direction finding.⁴⁵ A later paper by this author discussed the problem of finding an optimal excitation function for an electronically scanned array.⁴⁶ Finally, he derived an excitation function for an array with a known distribution of external interference.⁴⁷ The optimization criterion is the signal-to-noise ratio on the desired point source. This paper is relevant because one of the most severe problems in OTH radar is suppression of extraneous signals.

One Soviet antenna that has been the object of speculation as regards its role in an OTH system could be described as "arc-shaped." A paper by D. I. Voskresenskiy and A. I. Gudzenko discussed the characteristics of a pencil-beam arc-shaped array.⁴⁸ This theoretical array, with the radius large and element spacing small with respect to the wavelength, is directional in two planes, a desirable characteristic for an OTH radar. The paper explored the relationships between excitation functions, element directivity, and array directivity and found that the antenna had a higher directive gain than that of a linear antenna of length equal to the chord of the arc. Voskresenskiy and V. S. Filippov studied the problem of directivity of convex pencil-beam antennas with given magnetic currents on an ideally conducting surface of arbitrary shape whose characteristic dimensions and curvature radii sig-

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nificantly exceeded the wavelength.⁴⁹ A solution to the problem was obtained by taking into account the shielding effect of the conducting surface. It was shown that the maximum directive gain of a convex pencil-beam antenna, except in the case of super-directivity, was equal to that of an equivalent plane cophase aperture with a uniform amplitude distribution of colinear currents.

Detection Techniques and Resolution

Regardless of the radar concept employed, a basic feature of many OTH detectors is the use of Doppler velocity (or phase history), either to provide a discrimination from fixed background scatterers or from the illumination signal or to facilitate implementation of a filter matched to the transmitter waveform. Since the Doppler frequency shift itself and changes in the shift with time are not precisely known, it is necessary to employ one of three methods of matching the receiver to the target signal: multiple parallel receivers may be employed; a single receiver may be tuned through the expected Doppler band; or a small number of receivers may be located within the band spaces so that the change in Doppler shift with time will eventually cause the signal frequency to match that of one or more receivers. These receivers may employ narrow-band filters, delay lines, digital filter equivalents, or phase-locked loops, each with attendant advantages and limitations. None of the above techniques require a breakthrough in technology, but rather the application of existing technology.

Because of the geometry and the radar cross section of the target and the HF environment, the signal-to-noise ratio at the receiver input is usually poor in OTH radar, necessitating integration to achieve levels adequate for reliable detection. One technique employed with electronically scanned antennas is sequential detection. In this method the scan is interrupted if a suspected signal exceeds a threshold. Integration is performed until the signal either exceeds a higher threshold, or the signal falls below a lower threshold. A. S. Tyslyatskiy has discussed sequential detection in a receiver with sampling of a number of parallel channels. He derived an equation that defines the receiver performance and established values for the upper and lower threshold.⁶¹ The multiple channels could be sequentially scanned azimuth positions of the antenna, range bins in a modulated cw system, or Doppler channels. Prof. Ya. S. Itakhoki has also written a number of papers in the field of sequential detection and the coincidence of random pulse trains. Two of these papers have more than routine applicability to the fabrication of a sequential detector for an OTH radar.⁶²⁻⁶³

Digital computers, although their performance is not ideal, have been employed in detecting OTH

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signals because they can be programmed to process amounts of signal data impractical in analog equipment. Yu. B. Chernyak has written a paper that is closely related to this problem.⁶⁴ R. L. Drabkin in another interesting paper in the field of digital detection discussed a digital processor associated with a receiver in which the time available for processing by the computer is very short.⁶⁵ This could correspond to a computer engaged in beam steering and evaluating threat/target parameters or engaged in processing the data from a number of parallel channels.

A unique concept was expounded in a book by A. A. Abramyan which dealt with the theory of "asynchronous reception of pulse radar signals," and with the design of HF and superhigh frequency asynchronous detectors.⁶⁶ The claims made by the author could imply the use of a novel receiver design applicable to OTH radar where the problems of variable range delay and radio frequency interference can be limitations to performance.

Phase-locked loops, or as the Soviets call them, phase automatic frequency control (PAFC) can be of high utility in tracking OTH signals. The concept entails synchronizing an oscillator to the received signal and following Doppler shifts by controlling the frequency of the heterodyne oscillator with the phase error between the reference and incoming signal. With this technique the receiver can be made to have a very small noise bandwidth corresponding to the dynamic components of target motion rather than to modulation imposed on the transmitted signal to achieve range resolution. In addition, with PAFC systems it is possible to achieve a very high degree of unwanted-carrier suppression, which is important in most OTH radar problems. N. K. Kul'man and R. L. Stratonovich have discussed the application of PAFC's to the problem of measuring signal parameters with nonconstant phase and/or frequency.⁶⁷ A somewhat similar paper, which considered the ability of a signal processor to detect modulated signals in the presence of Doppler shifts, was written by Yu. N. Bakayev and A. A. Guzh.⁶⁸

OTH radar systems must operate in an adverse environment of clutter and extraneous interfering signals. For this reason the resolution properties

of the waveform and of the antenna beam are significant factors in OTH performance. L. P. Syosoyev has estimated signal parameters, including range and Doppler shift, in which he took into account additive and multiplicative interference as when "a signal passes through an inhomogeneous medium."⁶⁹ V. V. Akindinov has discussed a concept for measurement in which coarse range data is obtained by the conventional pulse envelope—time delay method.⁷⁰

ORGANIZATIONS ENGAGED IN OTH-RELATED WORK

Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation, USSR Academy of Sciences (IZMIRAN)

This institute leads in the areas of ionospheric data reduction, preparation of predictions, and research directly underlying ionospheric propagation characteristics. Publications of the institute have shown that a continuing effort is being made to apply modern techniques of digital automatic data reduction to the conversion of experimental records so that forms useful for both scientific analysis and prediction of propagation conditions can be obtained. Another area of research at IZMIRAN of interest to OTH applications is that of ionospheric irregularities and their relation to signal fading, angular ray dispersion, and the like.

IZMIRAN is also the leading Soviet institute in the field of ionospheric sounding. It maintains field stations throughout the USSR where both vertical and oblique sounding measurements are taken. This work along with the data derived therefrom would be important to the development of an operational OTH system.

B. S. Shapiro, one of the institute's foremost researchers has been concerned with the problem of true-height reduction of ionospheric data. Another researcher, A. L. Galkin, has dealt with the problem of automatically digitalizing virtual-height frequency data. T. S. Kerblay has been interested in many of the problems connected with HF propagation in the ionosphere. Included in these problems are propagation in an inhomogeneous ionosphere, ionospheric signal fading, and electron density gradients.

Moscow State University

At Moscow State University the published work that is most likely to bear on possible OTH activity is related primarily to diffraction theory and the properties of waves reflected from an irregular ionosphere.

T. A. Gaylit and V. D. Gusev have conducted a theoretical study of diffraction from a screen assumed to be at ionospheric height. Gaylit has also reported on an experimental project connected with the above study.

Institute of Radio Physics and Electronics of the Ukrainian Academy of Sciences

L. G. Sodin and Yu. M. Bruk have described a broadband electronically steered HF radiotelescope designed and constructed by the institute. They have discussed the tapped delay line concepts probably used to steer the beam of the radiotelescope. These authors have also been concerned with the directivity, radiation efficiency, and mean power gain of electronically steered arrays.

Scientific-Research Radio Physics Institute at Gorkiy University

Optimal antennas for use in direction finding which make use of electronic scanning have re-

ceived considerable attention at this institution. Work has also been carried out on developing antennas with dual or selectable polarization. Yu. M. Zhidko has been involved with the application of phase monopulse to active and passive direction finding.

Other Institutions

Several other institutions have contributed toward the advancement of knowledge in the field of HF propagation which could have application to the development of an OTH system. Among these are Gorkiy State University where studies of irregularities in the F region, of horizontal tilts in the ionosphere, and of ionospheric diffraction phenomena and absorption could have an underlying OTH orientation. The Ionospheric Department of the Academy of Sciences Kazakh SSR and Rostov-on-Don State University have published work on computer scaling of ionograms. The Kazakh Academy also has published work on the vertical drift of ionospheric inhomogeneities. A study of fading and signal correlations and of the origin of irregularities has been made at the Siberian Physico-Technical Institute of Tomsk State University.

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ABBREVIATION	TITLE
REEP	Radio Engineering and Electronic Physics
GA	Geomagnetism and Aeronomy
TRE	Telecommunications and Radio Engineering

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